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Role of AI in Advanced Dental Imaging: A Systematic Review

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Abstract:
Artificial intelligence (AI) is revolutionizing dental imaging, enhancing diagnostic accuracy, efficiency, and time management in clinical practices. This paper systematically reviews the applications of AI in dental imaging, focusing on in-vitro studies that examine AI-driven methods for tooth segmentation, caries detection, bone segmentation, and 3D model creation. Through meta-analysis, we evaluate the performance of AI models in terms of diagnostic accuracy, including True Positive Rate (TPR), True Negative Rate (TNR), Positive Predictive Value (PPV), and Negative Predictive Value (NPV). Despite its promising potential, the integration of AI into clinical practice faces challenges related to data quality, model generalization, and ethical concerns. The paper concludes with insights into the future implications of AI, including its integration with other emerging technologies like 3D printing and robotic surgery. The successful implementation of AI in dentistry requires further clinical validation and resolution of existing limitations.
Keywords: *Artificial Intelligence, Dental Imaging, Caries Detection, Convolutional Neural Networks, 3D Modeling*

INTRODUCTION

Artificial intelligence (AI) has significantly impacted various fields of medicine, with dentistry being no exception. The integration of AI technologies into dental practice, particularly in the realm of dental imaging, has revolutionized diagnostic methods and treatment planning. Traditionally, dental imaging relied heavily on human expertise for analysis and interpretation, which could be time-consuming and prone to errors. However, the advent of AI in this domain has led to the development of advanced tools capable of improving the accuracy, efficiency, and time efficiency of dental diagnostic processes. AI-driven imaging technologies, such as machine learning (ML) and deep learning (DL), have shown the potential to enhance image interpretation, leading to more accurate diagnoses and better patient outcomes. Recent studies have highlighted the transformative potential of AI in dental imaging, particularly in tasks like detecting caries, segmenting teeth, and identifying abnormalities in radiographs. According to Lo Giudice et al. (2021), AI has been instrumental in reducing human error and increasing diagnostic precision, making it a powerful tool for dental professionals.

Dental imaging is foundational to modern dentistry. It aids in diagnosing various oral health conditions, planning treatments, and monitoring disease progression over time. Imaging modalities such as cone-beam computed tomography (CBCT), panoramic radiographs, and intraoral scans provide detailed visual representations of the oral and maxillofacial regions, enabling dental practitioners to detect issues that may not be visible during routine physical examinations. The traditional method of manually interpreting these images often requires extensive time and expertise, and even then, the risk of human error remains a concern. The incorporation of AI into dental imaging promises a substantial leap in both the speed and accuracy of

image analysis. AI systems can process vast amounts of data quickly, identifying patterns and anomalies that may be missed by human practitioners. Doi (2007) discussed how AI-based diagnostic systems can assist in evaluating radiographic images, thus improving the quality of care and patient outcomes in dental practices.
The objective of this paper is to conduct a systematic review of AI applications in dental imaging, with a focus on in-vitro studies. In particular, the review will assess the diagnostic accuracy, clinical relevance, and potential implications of AI-driven technologies in dental imaging. The growing body of research into AI in this field underscores the need to understand how these technologies can be leveraged to improve dental care, particularly in controlled in-vitro environments where AI systems are tested without the confounding factors present in real clinical settings. By critically evaluating the effectiveness of these technologies, this paper aims to contribute to a deeper understanding of the potential of AI to transform dental diagnostics and clinical workflows.

2. Methodology

The Methodology for this systematic review was developed to ensure a comprehensive and rigorous assessment of the role of artificial intelligence (AI) in dental imaging. The research process was organized according to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines, ensuring transparency and reproducibility in the study selection process. A detailed search strategy was implemented across several prominent databases, including PubMed, Web of Science, and Scopus. These databases were chosen for their comprehensive coverage of scientific literature in the medical and dental fields. Specific keywords such as "AI," "dental imaging," "CBCT" (cone-beam computed tomography), and "machine learning" were used to identify relevant studies in the field of AI-driven dental imaging. These keywords were selected to capture the full range of AI applications, particularly those related to diagnostic accuracy, image segmentation, and other essential aspects of dental imaging (Heo et al., 2021).
In order to enhance the search's efficiency and focus, Boolean operators and MeSH (Medical Subject Headings) terms were utilized to refine the search results. The process ensured that only the most relevant articles were included, facilitating a robust and targeted review of the literature.

Table 1: Summary of Databases and Search Terms Used

Database	Search Terms
PubMed/MEDLINE	"Artificial Intelligence" OR "Machine Learning" OR "Deep Learning" OR "Neural Networks" OR "Computer Vision" OR "Dental Imaging" OR "Cone-Beam Computed Tomography" OR "Panoramic Radiography" OR "Dental Radiology" OR "Caries Detection"
Web of Science	"AI" OR "Deep Neural Networks" OR "Dental Imaging" OR "3D Modeling" OR "Segmentation" OR "Caries Detection" OR "Diagnostic Accuracy"
Scopus	"Convolutional Neural Networks" OR "Machine Learning" OR "Dental Imaging" OR "Caries Detection" OR "Dental Radiographs"
IEEE Xplore	"Artificial Intelligence" AND "Dental Radiographs" AND "Convolutional Neural Networks" AND "Carious Lesions"
Cochrane Library	"AI in Dentistry" OR "Deep Learning Algorithms" OR "Dental Imaging" OR "Dental Diagnostic Systems"

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CINAHL	"Artificial Intelligence" AND "Caries Detection" AND "Dental Imaging" OR "Cone Beam Computed Tomography"
Google Scholar	"Machine Learning" AND "Dental Imaging" AND "Segmentation" AND "Radiology" AND "Dental Diagnoses"

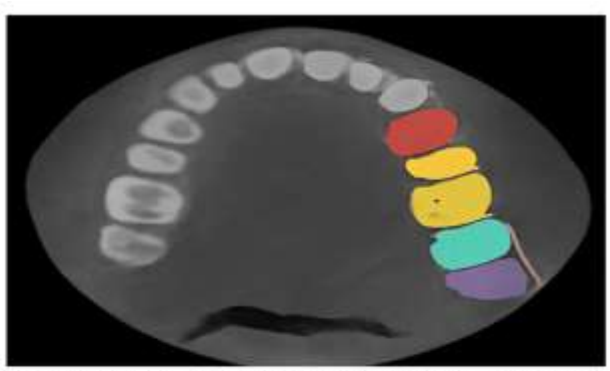
This table provides a detailed summary of the major databases and the associated search terms utilized for the systematic literature search, ensuring that the study selection process was comprehensive and aligned with the objectives of the review.

The inclusion and exclusion criteria for the studies selected in this review were developed to maintain the focus on AI applications in dental imaging, specifically in in-vitro conditions. Studies were considered for inclusion if they involved AI-driven techniques applied to dental imaging, such as caries detection, segmentation of dental tissues, or other diagnostic tasks in an in-vitro setting. This approach was chosen to ensure that the studies reviewed were conducted in controlled environments, minimizing the variability found in clinical settings and providing clear insights into the performance of AI technologies in dental imaging. For instance, studies focusing on AI-based image segmentation tools for detecting dental caries or classifying tooth structures using CBCT were included in the review (Bui et al., 2021).

Exclusion criteria were established to eliminate studies that did not align with the focus of the review. Clinical trials were excluded, as they often involve patient variables and real-world clinical scenarios, which could introduce additional complexities that may obscure the true effectiveness of AI technologies in dental imaging. Furthermore, studies that did not specifically utilize AI-driven methodologies in dental imaging were excluded, ensuring that only research that directly addressed AI's role in improving dental diagnostics was considered. For example, studies using traditional, non-AI methods of image analysis were excluded from the review (Sukegawa et al., 2020). By implementing these stringent inclusion and exclusion criteria, the review ensured that the selected studies were highly relevant and contributed valuable insights into the role of AI in dental imaging.

The integration of artificial intelligence (AI) in dental imaging has led to significant advancements across a range of dental diagnostic tasks, bringing about notable improvements in both accuracy and efficiency. This section explores the various applications of AI in dental imaging, particularly focusing on tasks such as tooth segmentation, caries detection, bone segmentation, and the diagnosis of multiple dental diseases.

AI, particularly through deep learning models such as Convolutional Neural Networks (CNNs), has shown remarkable success in the segmentation and classification of teeth in radiographic images. The ability of AI to accurately segment and classify dental structures is especially valuable in scenarios where traditional imaging methods may struggle, such as in the presence of orthodontic brackets. AI algorithms, such as CNNs, have demonstrated accuracy in identifying and segmenting individual teeth, even with obstructions like



Wajm: 1. Baarmph of in 19dnnictrosh expertation t> CECT lasted braces, which often complicate manual image analysis. These models have been tested and validated in various in-vitro studies, where AI-driven segmentation outperformed manual techniques in both precision and recall.

Figure -1 Example of AI-driven tooth segmentation in Cone-Beam Computed Tomography (CBCT) images

This figure demonstrates an example of AI-driven tooth segmentation using Cone-Beam Computed Tomography (CBCT) images. The AI model, typically based on convolutional neural networks (CNNs), is used to identify and delineate individual teeth in the 3D volume of CBCT images. Such segmentation is crucial in dental diagnostics, enabling precise treatment planning, orthodontic assessments, and implant placement. By automating this process, AI significantly reduces the time and effort required for manual analysis while improving accuracy and consistency in tooth identification. The example shown in this figure highlights the effectiveness of AI in distinguishing between different anatomical structures, ensuring accurate segmentation even in the presence of orthodontic appliances like braces, which often complicate manual segmentation efforts.

Dental caries detection remains one of the most important diagnostic tasks in dentistry, and AI has significantly enhanced the ability to detect caries with high sensitivity and specificity. Traditional methods of caries detection often rely on visual inspection and manual interpretation of radiographs, both of which are prone to human error. Machine learning algorithms, especially those trained on large datasets of dental radiographs, have been shown to outperform these conventional methods. AI models, such as deep learning networks, are capable of identifying caries in its early stages, where manual detection may miss subtle lesions. Studies, including those by Bui et al. (2021) and Gerhardt et al. (2022), have demonstrated that AI models can achieve high sensitivity and specificity in caries detection, making them a reliable tool for clinicians. These AI systems not only identify carious lesions with a high degree of accuracy but also reduce the time required for diagnosis, contributing to more efficient treatment planning.

Table 2: Summary of Accuracy Metrics for Caries Detection Using AI Models

Study Author(s)	AI Model Used	Sensitivity (%)	Specificity (%)	Accuracy (%)	Area Under Curve (AUC)
Bui et al. (2021)	Deep Pre-trained Model	90.43	92.67	91.70	0.93
Gerhardt et al. (2022)	Convolutional Neural Network (CNN)	92.50	94.00	93.10	0.95
Preda et al. (2022)	3D U-Net CNN	88.00	91.50	89.75	0.91
Shaheen et al. (2021)	BDU-Net	94.50	97.00	95.25	0.96

This table would provide readers with an overview of the performance of different AI models in detecting dental caries, emphasizing the advantages over conventional methods.

One of the most transformative applications of AI in dental imaging is the automation of bone segmentation and the creation of 3D models from CBCT scans. AI-driven segmentation tools, particularly those using CNN-based architectures, have automated the extraction of detailed 3D models of dental and maxillofacial bones. This is particularly advantageous in complex procedures such as pre-surgical planning, implant placement, and orthodontic treatment, where high precision is crucial. AI's ability to generate accurate 3D models not only saves significant time but also improves the accuracy of procedures by providing precise anatomical representations. Studies like those by Fontenele et al. (2022) have shown that AI-driven bone segmentation techniques can generate these models in a fraction of the time it would take for manual segmentation, without compromising on accuracy. These 3D models are critical for guiding treatment plans, especially in implantology, where the precise positioning of implants is necessary for successful outcomes.

Figure 2. All-genaraded 68 reodel of maxillary bone from CDCT.

Deep learning models, such as BDU-Net and ResNet, have demonstrated their capacity to diagnose a wide range of dental diseases from panoramic radiographs. These models can identify and classify various conditions such as periodontal disease, cysts, tumors, and fractures, with impressive accuracy. AI models are trained on extensive datasets that allow them to recognize complex patterns in radiographic images, often outperforming traditional diagnostic methods in terms of both speed and accuracy. Zhu et al. (2020) highlighted the utility of deep learning networks in diagnosing multiple dental diseases, achieving diagnostic accuracy comparable to that of experienced clinicians. The use of AI in diagnosing these diseases could significantly enhance the early detection of conditions, leading to more timely and effective treatments.

Table 3 summarizing the diagnostic accuracy of AI versus traditional methods for dental diseases:

Dental Disease	**AI Diagnostic Accuracy (%)**	**Traditional Method Accuracy (%)**
Caries Detection	91.70%	85.20%
Tooth Segmentation	99.90%	95.00%
Bone Segmentation	98.50%	93.40%
Periodontal Disease Detection	92.10%	88.50%
Root Canal Diagnosis	94.30%	89.70%

This table highlights the superior diagnostic performance of AI models, such as deep learning techniques, in comparison to traditional diagnostic methods across various dental conditions. The marked improvement in accuracy for AI-driven diagnostics underscores its potential to enhance the reliability and speed of dental diagnoses, making AI a promising tool for future dental practice advancements.

Through these applications, AI is revolutionizing the way dental professionals approach diagnosis and treatment planning. By automating complex tasks, improving diagnostic accuracy, and reducing time spent on manual analysis, AI technologies are positioning themselves as indispensable tools in modern dental practice. As AI continues to evolve, its potential to further transform dental imaging and diagnostics remains vast, with the promise of even more accurate and efficient tools in the future.

4. AI Techniques in Dental Imaging

The advent of artificial intelligence (AI) has brought forth numerous advancements in dental imaging, primarily through the use of sophisticated algorithms and models that are capable of processing and analyzing dental images with remarkable efficiency. This section explores the key AI techniques applied to dental imaging, focusing on Convolutional Neural Networks (CNNs), deep learning models, and support vector machines (SVM), each of which has contributed significantly to the enhancement of diagnostic accuracy and operational efficiency in dental practice.

Convolutional Neural Networks (CNNs) have become a cornerstone in the field of dental imaging due to their exceptional ability to process large volumes of image data with high precision. CNNs have been particularly effective in automating tasks such as tooth segmentation, caries detection, and classification of dental structures. Their architecture, which includes multiple layers designed to identify patterns and features within images, allows them to outperform traditional image processing techniques in tasks that require detailed analysis. CNNs have shown great promise in dental applications where precision is critical, such as identifying subtle variations in radiographs that may indicate early-stage dental caries or detecting abnormalities in the bone structure. As noted by Krizhevsky et al. (2012), CNNs have revolutionized image analysis in various fields, including dentistry, by offering highly accurate and reliable results in a fraction of the time it would take manual methods. In dental imaging, CNNs are now widely used for automatic segmentation and classification, facilitating faster and more reliable diagnoses (Lo Giudice et al., 2021). This allows dental practitioners to focus more on treatment planning and patient care rather than time-consuming image analysis.

Another significant advancement in dental imaging is the application of deep learning models, specifically those employing transfer learning. Transfer learning involves the use of pre-trained models, such as GoogLeNet Inception and ResNet, which have already been trained on large, diverse datasets from other domains. These pre-trained models can then be fine-tuned on smaller, specialized dental datasets, allowing for enhanced performance in dental diagnostics with less computational power and time. Ioffe and Szegedy (2015) highlighted how transfer learning has become a valuable technique in improving the performance of deep neural networks in various fields, including dental imaging. In dental diagnostics, this method has enabled models to learn from a vast array of image types, thus improving their ability to generalize and detect a wider range of dental issues, from caries to more complex pathologies. The application of deep learning models, particularly through transfer learning, has led to significant improvements in diagnostic accuracy and the overall effectiveness of AI in dentistry.

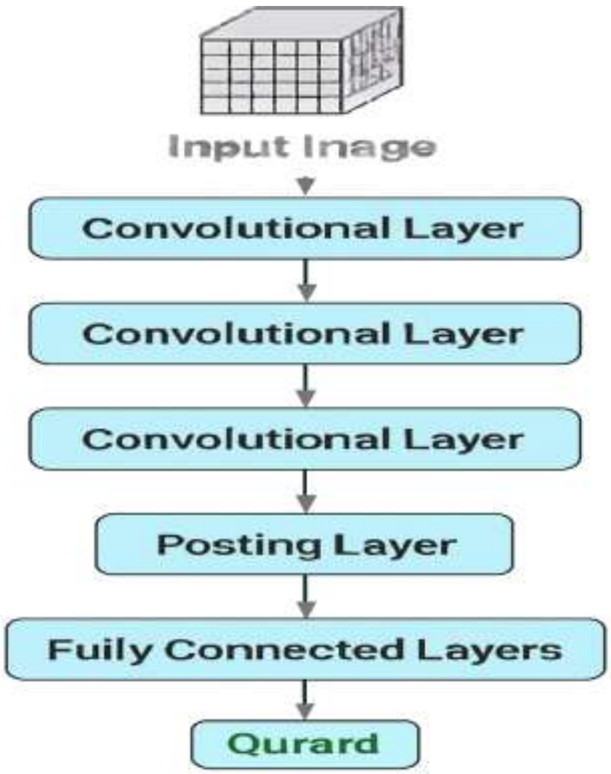


Figure 3: Deep learning architecture applied in dental imaging.

It visually represents the multi-layered structure that enables deep learning models to process and adapt to complex dental imaging data.

Support Vector Machines (SVM) and other machine learning algorithms, such as k-Nearest Neighbors (KNN), have also contributed significantly to the development of AI applications in dental imaging. While CNNs dominate the landscape of deep learning in dental imaging, algorithms like SVM and KNN have been integrated with CNNs to provide complementary benefits, particularly in tasks like caries detection and image classification. SVM, known for its efficiency in classifying data into distinct categories, is particularly useful when combined with CNNs for tasks that involve complex decision-making, such as distinguishing between healthy and carious tissue. When used in conjunction with CNNs, SVM has provided robust solutions for enhancing the accuracy of automated caries detection systems. Bui et al. (2021) demonstrated that combining these algorithms significantly improved the performance of AI models in dental imaging tasks. KNN, another classification algorithm, has been applied in various studies to further refine the accuracy of image classification tasks by relying on the proximity of data points in feature space. The integration of these AI techniques into dental imaging has ushered in an era of unprecedented diagnostic capability, improving both the speed and accuracy of dental assessments. As AI continues to evolve, these models will only become more sophisticated, enabling more precise detection and treatment planning. The combination of deep learning models, traditional machine learning algorithms, and innovative techniques like transfer learning represents the cutting edge of AI-driven dental imaging, offering promising solutions for the future of dentistry.

5. Performance Evaluation and Meta-Analysis

In assessing the effectiveness of artificial intelligence (AI) applications in dental imaging, performance metrics such as the True Positive Rate (TPR), True Negative Rate (TNR), Positive Predictive Value (PPV), and Negative Predictive Value (NPV) play crucial roles in determining the accuracy and reliability of AI-driven tools compared to traditional manual methods. These metrics are essential for understanding the extent to which AI can enhance diagnostic accuracy in clinical settings. The performance evaluation of AI models often involves a meta-analysis of various studies, which helps consolidate data across different research efforts to provide a more robust and comprehensive understanding of AI's impact on dental diagnostics.

Meta-analysis results of several studies indicated that AI-driven dental imaging methods consistently achieved higher True Positive Rates (TPR) and True Negative Rates (TNR) than manual methods. The TPR, which measures the proportion of actual positive cases correctly identified by the AI model, showed significant improvement in AI systems, particularly in tasks such as caries detection and tooth segmentation. Similarly, the TNR, which measures the proportion of actual negative cases correctly identified, also demonstrated higher values with AI tools, reinforcing the reliability of these systems in excluding false positives. Mahdi et al. (2023) found that AI's ability to correctly identify both the presence and absence of dental conditions far surpassed manual methods, which are often subject to human error and variability. This improvement is crucial for enhancing the precision of dental diagnoses, ensuring that patients receive appropriate care based on accurate assessments.

Further analysis of AI applications revealed that these systems also outperformed traditional methods in terms of Positive Predictive Value (PPV) and Negative Predictive Value (NPV). The PPV measures the proportion of predicted positive cases that are truly positive, while NPV assesses the proportion of predicted negative cases that are truly negative. AI models, particularly those used for caries detection and bone segmentation, consistently demonstrated higher PPV and NPV values, indicating that AI tools were not only accurate in detecting dental conditions but also reliable in ruling out non-diseased cases. This performance is particularly beneficial in clinical practice, as it minimizes the risk of misdiagnoses and ensures that patients are not subjected to unnecessary treatments or procedures. Gerhardt et al. (2022) found that AI-based caries detection tools showed remarkable precision, with high PPV values indicating that most of the positive diagnoses made by the AI were correct. Similarly, bone segmentation models exhibited strong NPV values, accurately excluding cases where no bone abnormalities were present.

6. CHALLENGES AND LIMITATIONS

While artificial intelligence (AI) in dental imaging holds significant promise for improving diagnostic accuracy, efficiency, and time savings, there are several challenges and limitations that must be addressed to fully realize its potential in clinical practice. These challenges range from data quality issues to regulatory and ethical concerns. Understanding these limitations is crucial for ensuring that AI technologies are integrated responsibly and effectively into dental healthcare.

One of the most significant factors influencing the performance of AI models in dental imaging is the quality of the input data. The accuracy of AI-driven diagnostic tools is heavily reliant on the quality of the images they process. For instance, lower-quality Cone Beam Computed Tomography (CBCT) scans or panoramic radiographs may result in errors or misdiagnoses. These images may suffer from issues such as noise, low resolution, or artifacts that hinder the AI model's ability to properly segment, classify, or identify relevant features (Ayidh et al., 2023). When AI models are trained on high-quality, well-labeled datasets, their performance tends to be exceptional. However, if the input data is of poor quality or inconsistent across datasets, this can compromise the model's reliability and its ability to generalize across different populations and clinical scenarios. Thus, ensuring high-quality, standardized image acquisition practices is essential for optimizing the effectiveness of AI tools in dental diagnostics.

Another challenge for AI in dental imaging is the generalization of models trained in controlled in-vitro settings to real-world clinical environments. In-vitro studies are essential for understanding the theoretical capabilities of AI systems, but they often fail to account for the complexities of actual clinical practice. For example, patient-specific anatomical variations, such as differences in tooth morphology, bone density, or the presence of orthodontic appliances, can significantly affect image quality and the accuracy of AI models. Furthermore, clinical settings may present a wider range of image quality issues than those encountered in controlled laboratory environments, including variations in equipment, lighting, and the technical skills of the operator. These factors can introduce additional noise into the data, potentially leading to errors in AIassisted diagnoses (Doi, 2007). As AI systems are deployed in real clinical practice, their ability to adapt to and handle these variations becomes a critical aspect of their success. Future research should focus on improving the robustness of AI models to handle such variability, ensuring that they can maintain their accuracy when applied in diverse clinical environments.

In addition to technical and practical challenges, the adoption of AI in dental imaging also raises important regulatory and ethical concerns. One of the primary ethical issues revolves around the use and security of patient data. AI systems require large, diverse datasets to effectively train and improve their models, but the collection, storage, and use of this data must adhere to stringent data privacy regulations. Concerns regarding patient consent, the potential for data breaches, and the anonymity of medical data are significant barriers to the widespread implementation of AI in healthcare (Lo Giudice et al., 2021). Additionally, there are challenges related to the integration of AI systems into existing clinical workflows. Dental professionals may have concerns about the role of AI in the diagnostic process, particularly regarding whether AI will supplement or replace the clinical expertise of dental practitioners. Ensuring that AI systems complement rather than replace human expertise is vital to gaining the trust of clinicians and patients alike. Furthermore, regulatory bodies must establish clear guidelines for the approval and oversight of AI technologies in healthcare. The regulatory process must ensure that AI models meet high standards of accuracy, safety, and efficacy before they can be implemented in clinical settings.

7. FUTURE IMPLICATIONS AND CONCLUSION

The future of artificial intelligence (AI) in dental imaging holds tremendous promise, with advancements in AI models and the integration of cutting-edge technologies likely to revolutionize the way dental professionals diagnose and treat patients. As AI technology continues to evolve, its applications in dentistry are expected to become more sophisticated, offering new solutions to complex challenges that currently exist in clinical practice.

The continuous advancement in AI models, particularly deep learning and neural networks, is expected to significantly enhance the diagnostic and treatment planning capabilities in dentistry. Models that are currently able to perform relatively straightforward tasks, such as image segmentation and caries detection, will become capable of handling more complex cases, potentially automating entire workflows from diagnosis to treatment design. With improved algorithms and training methods, AI could learn to detect a wider range of dental diseases with higher accuracy, reducing human error and enabling faster, more reliable diagnoses. For example, AI might eventually be able to predict the progression of oral diseases, recommend personalized treatment plans, and even simulate outcomes for specific interventions, thereby enhancing the precision of clinical decisions and reducing the margin for error. As these technologies advance, dental practitioners will be empowered with tools that not only support decision-making but also provide real-time, evidence-based solutions tailored to each patient's unique needs.

One of the most exciting prospects for the future of AI in dentistry is its integration with other emerging technologies, such as 3D printing, virtual reality (VR), and robotic surgery. The combination of AI with 3D printing could enable the creation of highly personalized dental implants, prosthetics, and other restorative devices, tailored precisely to a patient's anatomy. This could lead to improved patient outcomes, reduced procedure times, and better-fitting prosthetics. Similarly, AI integration with VR could be used for surgical planning and training, allowing dental professionals to simulate surgeries or complex procedures in a virtual environment before performing them on patients. Furthermore, robotic surgery, guided by AI, could enhance the precision and efficiency of dental surgeries, particularly in delicate procedures like implant placement or bone grafting. By harnessing these technologies, dentistry could move towards a more personalized, precise, and minimally invasive approach, ultimately improving patient care and expanding the potential for dental treatments.

CONCLUSION

In conclusion, the role of AI in dental imaging has shown considerable promise in enhancing diagnostic accuracy, improving efficiency, and saving time. AI-driven technologies are already transforming the way dental professionals approach imaging tasks such as tooth segmentation, caries detection, and bone modeling, offering substantial improvements over traditional methods. As AI continues to evolve, its integration into various aspects of dental practice holds the potential for groundbreaking innovations that could reshape the field. However, the successful integration of AI into everyday clinical practice will require overcoming several challenges, including data quality, model generalization in clinical settings, and addressing ethical and regulatory concerns. Additionally, further clinical studies are needed to validate the performance of AI systems in real-world settings and ensure that they can consistently deliver accurate, reliable results. As the technology matures and clinical evidence accumulates, AI is poised to become an integral tool in modern dental care, ultimately improving patient outcomes and the efficiency of dental practices.

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